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Fast and accurate measurement of the dispersion of cascaded components

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Abstract: We show that the dispersion of multiple cascaded components can be determined from a single low-coherence interferometric measurement. This measurement is not adversely affected by other components in the system, regardless of their wavelength reflection bands.

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1. Introduction

Low-coherence interferometry has several advantages over conventional techniques such as the modulation-phase-shift method [1] for the characterization of components such as fiber Bragg gratings (FBGs). A key advantage is the rapidity with which a measurement of group delay and reflectance can be obtained. The interferogram is obtained in less than a second, and processing the interferogram to obtain group delay or reflectance takes less than 60 seconds [2], compared with the conventional modulation-phase shift measurement, which can take several hours [1].

In this paper, we demonstrate the measurement of the dispersion of cascaded components using low-coherence interferometry [3]. From that same measurement, we show that the physical separation between the components can also be determined. We also show that the group-delay measurement is not adversely affected by other reflective components in the system, regardless of overlapping reflection bands. This is important for fiber optic telecommunications applications where several gratings are used in series as add/drop multiplexers [4] and in cases where several gratings are concatenated to achieve desired dispersion characteristics [5].

2. Measurement Method

A diagram of the low-coherence interferometric system is shown in Fig. 1. A broadband erbium (Er) superfluorescent fiber source (SFS) provides the input signal. Fiber coupler 1 provides a comparison signal for the difference-over-sum (Δ/Σ) amplifier, as explained below. Fiber coupler 2 is part of a Michelson interferometer. Three FBGs are spliced onto the test arm of the interferometer. FBGs A and C have overlapping reflection bands; therefore, fiber coupler 3 separates these two gratings to eliminate Fabry-Perot and shadowing effects.

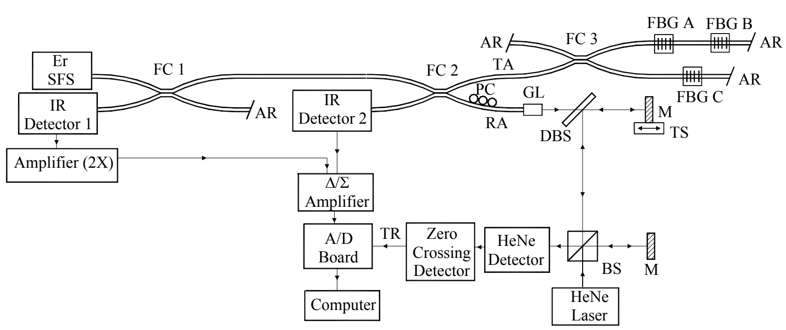

Figure 1. Diagram of low-coherence interferometric system for measuring the dispersion of multiple FBGs. AR: anti-reflection coating, FC: fiber coupler, RA: reference arm, TA: test arm, PC, polarization controller, GL: grin lens, M:mirror, TS: translation stage, BS: beamsplitter, DBS: dichroic beamsplitter, Δ/Σ: difference over sum.

The reference arm of the interferometer contains a variable-length air path so that the total optical path difference (OPD) of the interferometer can be varied. A frequency-stabilized HeNe-laser interferometer monitors the position of the reference-arm mirror, and a zero-crossing circuit triggers sampling of the IR signal on positive-sloped zero crossings of the HeNe signal.

The light from the reference arm is recombined with the light from the test arm at fiber coupler 2, and the recombined light is directed onto the two IR detectors. The detected signals have similar source excess-noise characteristics, while the interference terms are 180º out of phase due to coupler 1. Therefore, using a Δ/Σ amplifier will reduce excess noise from the SFS, which is the dominant noise source. This improves the interferogram's signal-to-noise ratio by a factor of 3, and yields a corresponding improvement in the group-delay SNR.

If the effective spatial separation between the FBGs exceeds the width of the individual coherence functions, then the output signal of the Δ/Σ amplifier, as a function of OPD, consists of three distinct signatures. Each of these signatures represents the interference of light reflected from one of the FBGs with light reflected from the reference-arm mirror.

The shape and extent of the interferometric signatures from FBGs A and C are determined by their reflection characteristics. To calculate the reflection group delay from the interferometric signatures, we first window the interferogram data around the interferometric signature of interest. Next, we append zeros to the array (zero padding) to obtain an array of length 2^N. The choice of N determines the wavelength resolution of the group-delay results. Larger values of N give better resolution, but if N is too large, computational errors such as roundoff error will affect the accuracy of the results. For the results shown in this paper, we use N=18, giving a wavelength resolution of 14 pm. To obtain the group delay, we take the Fourier transform of the truncated and padded interferogram. The magnitude of the Fourier transform is proportional to the magnitude of the field reflection coefficient of the FBG. The relative group delay of the FBG is determined by differentiating the phase of the corresponding Fourier transform.

The light transmitted by grating A and reflected by grating B sees the effects of both gratings A and B, but the processing to obtain the group delay is the same. We take the Fourier transform of the interferometric signature, and then we differentiate the phase of the Fourier transform. The resultant group delay is the product of the reflection group delay of B with the double-pass transmission group delay of A.

We also measured the transmission group delay of a single grating using a variation of the system shown in Fig. 1. We replaced fiber coupler 3 and the three gratings with grating A spliced directly to the test arm of fiber coupler 2. We cleaved the far end of grating A's fiber pigtail to produce a Fresnel reflection. In this case, the interferogram consisted of a pair of signatures. The first signature represents the interference of light reflected by grating A with light from the reference arm. The second signature represents the interference of light reflected by the cleaved endface with light from the reference arm. The transmission group delay can be obtained from the second signature by taking a Fourier transform of the signature, and then differentiating the phase of the Fourier transform to obtain the double-pass transmission group delay.

We also calculated the physical separation distance between gratings from the multiple grating interferogram. We first accurately determine the central fringe of each interferogram through a Fourier transform technique [6]. The separation between the central fringes is equal to the product of the physical separation between interferograms with the group index of the fiber. Using the group index from the fiber specifications, the physical separation between gratings can be determined.

3. Experimental Results

We used our interferometric system to determine the reflection group delay of three gratings. The center wavelengths, reflection bandwidths, and reflectances of the three gratings are shown in Table 1. The interferogram in this case consisted of three distinct signatures created by interference of the light reflected by each grating with the light from the reference arm. From the separation between the interferometric signatures, we found that gratings A and B were separated by 6.95 cm of fiber, and the effective fiber separation between gratings A and C was 7.9 mm.

Table 1. Specifications of the three gratings.

Grating	Center Wavelength (nm)	Reflection Bandwidth , FWHM (nm)	Reflectance (%)
A	1555.6	5.4	99
B	1541.3	10.1	>97
C	1554.7	1.7	>99

Since gratings A and B are directly in series, any measurement of the reflection group delay of B will include the transmission group delay of A. We measured the transmission group delay of grating A by removing the other two gratings as described above. The results are shown in Fig. 2.

We also calculated the group delay of each of the three gratings from the three-grating interferogram. The group-delay results for these gratings are shown in Fig. 3. For gratings A and C, the group delay is simply the relative reflection group delay of the individual gratings. In the case of grating B's results, the group delay is the product of the reflection group delay of B with twice the transmission group delay of grating A. However, by comparing the double-pass transmission group delay of grating A from Fig. 2 with the group delay of B shown in Fig. 3, it is clear that the transmission group delay of A is negligible compared to the reflection group delay of B.

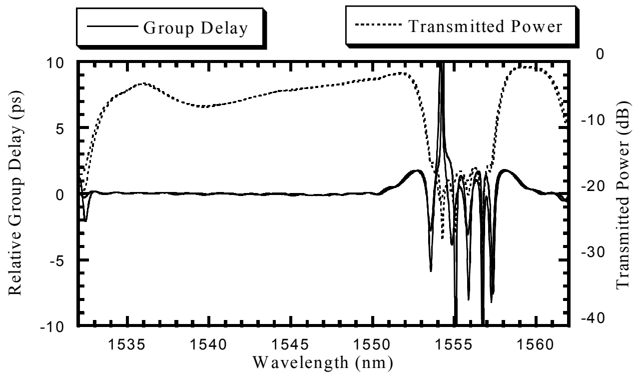

Fig. 2. Transmission group delay and relative power transmittance of FBG A. Results are shown from two repeated measurements.

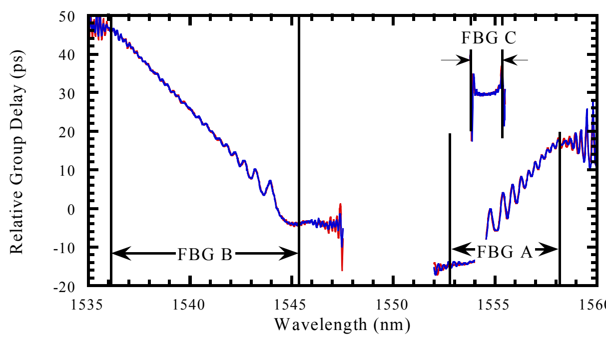

Figure 3. Group delay of three different gratings determined from a single measurement. To show this measurement's repeatability, the measurement was repeated and the second measurement results are also shown. The group delay values shown above are relative; there is an arbitrary group-delay constant added to each curve.

4. Conclusions

We have demonstrated the measurement of the group delay of multiple cascaded components using low-coherence interferometry. We have shown that the group delay of individual components in series can be determined regardless of overlapping reflection bands. This is unique to the low-coherence technique; conventional dispersion measurements are incapable of distinguishing between individual components with overlapping reflection bands. Another advantage of the low-coherence technique is speed; it is possible to obtain the group delay of multiple components in less than 60 seconds.

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